5.6 SMALL ENVIRONMENTAL RESEARCH AIRCRAFT: THE FUTURE OF AIRBORNE GEOSCIENCE

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1. INTRODUCTION

Research aircraft are essential for the investigation of the Earth and its atmosphere. Speed and three-dimensional freedom are their essential assets. These characteristics allow the efficient investigation of problems which have spatial distributions ranging vertically from the surface to the stratosphere and horizontally from a few meters to hundreds or even thousands of kilometers. Aircraft can assess the spatial variability over relatively large distances in a short period of time. Data acquired can address the representativeness of a point observation with respect to its surrounding area, especially over heterogenous regions and complex terrain. Understanding the spatial variability between ground-based observation points (i.e., subgrid variability) has important implications on weather and climate prediction.

Historically, large multi-engine aircraft were needed to carry the large, heavy, and power-hungry scientific instruments. While our understanding of the atmosphere grew with the use of large aircraft through the 1950's and 1960's, significant measurement uncertainties existed due to aircraft motion and flow distortion. With the advent of inertial navigation systems (INS), aircraft motion could be measured. In particular, motion-induced errors could now be removed from wind measurements (Holmes 1972;Lenschow 1986), however, large flow distortion errors still remained (Wynyard et al. 1985; Wyngaard 1988; Crawford et al. 1996). Throughout the 1970's and early 1980's, scientists rapidly developed new research sensors to probe the atmosphere and view the Earth's surface. These state-of-the-science sensors still lacked microprocessor controllers. Thus, large aircraft were still required.

Since mid-1980, impressive advances have been made in the development of smaller, faster, and more powerful microprocessors. Phenomenal increases in data storage capacity have also been seen. As a result, sensors and data acquisition systems became smaller, lighter, and consumed significantly less power. Advances in navigation systems such as OMEGA/VLF, LORAN-C, and currently global position system (GPS) have followed this same trend. For the first time, large aircraft were not required to carry a heavy payload of sensors, data acquisition systems, and multiple scientists. These emerging technologies have made it possible to use small aircraft for various types of research applications.

Large aircraft have a long and distinct history in sciences and have played an important role in many discoveries within the atmosphere. Unfortunately, the flight hour cost for a large multi-engine aircraft has become prohibitive for many applications and efficiency is further reduced by associated logistical complexities. While large aircraft are required for particular applications, there are many measurements that can be made more accurately from much smaller aircraft with state-of-the-science sensors and data acquisition systems at a fraction of the cost. We refer to this new high-technology mix of a high-performance small aircraft equipped with modern sensors and powerful computers as the Small Environmental Research Aircraft (SERA).

The SERA is a proven and cost-efficient airborne measurement system for acquiring high-fidelity data. State-of-the-science sensors and powerful data acquisition systems are automated and therefore require little supervision during flight. There are several types of small aircraft which are ideally suited for atmospheric research. These airframes are designed to minimize flow distortions that would otherwise corrupt various *in situ* measurements. These aircraft are also capable of flying at low altitudes and at slow speeds, a necessary requirement for air-surface exchange research. In addition, small aircraft are simpler to maintain and operate without sacrifices in safety. The acquisition and operating costs are one to two orders of magnitude *less* than large aircraft. The SERA does not require large support facilities or full-time professional pilots. In fact, the SERA requires a small team to successfully execute a research study. For the first time, small organizations with limited funding can afford to conduct highly-focused research studies with an airborne platform.

2. SERA

In concept, the SERA is a clever integration of modern scientific sensors, powerful computers, and a small single-engine aircraft. The SERA becomes a effective tool when used by a small science team in their investigations of the atmosphere and the Earth's surface. Due to its simple nature and a direct "hands-on" involvement by the scientist, the SERA is very adaptable and easily deployed. Cost-efficiency is also an important benefit.

2.1 *Concept*

The success of a SERA effort is critically dependent on the appropriateness of the chosen aircraft. We define the SERA as a single-engine aircraft which has a nominal weight of 300 to 600 kg. This excludes smaller "ultra-light" aircraft and the much heavier "light-twin" aircraft. Although the purchase and operational costs of an ultra-light aircraft can be enticing, as well as their associated mechanical and operational simplicity, their poor robustness in turbulent conditions and anemic payload capacity severely limits their utility as a SERA platform (Borys et al. 1983). Twin-engine aircraft are also excluded as a SERA because operational

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costs increase and complexities escalate rapidly with aircraft size.

Using an uncomplicated aircraft simplifies many aspects of operation in the field. SERA's small size and minimal infrastructure requirements permit low-cost operation from small general-aviation airports anywhere in the world. Larger airports can be avoided where longer ferry flights to the experiment site, air traffic delays, and higher costs add logistical complexity to a field study. While the pilot needs to maintain proficiency, flying a SERA is much simpler than a larger multi-engine airplane. The pilot can also be a team scientist, engineer, or a technician. This has the distinct advantage for scientific decision making during research flights. With SERA's pilot/scientist, the logistics of flight planning become simple and flexible. Field studies can be conducted with as few as two people: one person to pilot the SERA and the other providing ground support and communications during airborne missions. In contrast, a large multi-engine aircraft usually requires a pilot, copilot, and several flight crew members, thereby significantly increasing cost and complexity.

The simplicity of a SERA also makes operation at a home base easy. In this context, “simple” is strongly distinguished from "unsophisticated." Indeed, it is the sophistication of aircraft and electronics technology that allows the simplicity of SERA operations. Small research organizations can maintain a SERA from a small nearby general aviation airport. Since the SERA is a relatively simple platform, maintenance requirements can be easily secured at relatively small facilities. This flexibility allows quick and easy access for development and modification to the aircraft, sensors, and data acquisition systems. Fiberglass construction allows flexibility in modifying the airframe to mount sensors and instrument pods. Sensors, electronics, and data acquisition systems can be changed or modified to meet specific mission requirements with relative ease. A major emphasis is implementing the most current state-of-the-science instrumentation and electronics. Many of the required sensor and electronics are commercially available, thus simplifying replacement or repair. As a result of this convenience and simple aircraft maintenance, SERA scientists can commit more of their time and energy toward scientific planning and analysis.

While large aviation research facilities may find the SERA attractive for various applications, the main benefit is to small organizations that are unable to afford the research hours of a large aircraft. Operational costs for large aircraft are driven up by labor costs, facilities, and fuel consumption. Operational costs for a SERA, however, are greatly reduced since staff and facility requirements are minimal. The SERA will fill a strategic niche by exploiting a low-cost, high-utility aircraft that is an ideal platform to carry *in situ* and remote sensors. These sensors are also becoming smaller, lighter, more reliable, and most important, less expensive. The purchase price of a SERA (including basic avionic electronics) is between $100K and $200K. The cost of a suite of sensors varies greatly, ranging from less than $10K to $100K, depending upon the scientific application. Operational costs, without pilot, vary between $40 and $80 per hour.

2.2 *Aircraft*

Advances in aircraft construction, materials, design, and safety accessories enhance the utility of the SERA. In the past, scientists compromised their measurements with significant flow distortion errors on large aircraft. The high cost of a large aircraft required general purpose use. As a result, needed airframe modifications for sensor installation were discouraged. In contrast, the SERA is low-cost, often less than the cost of scientific instrumentation carried. As a result, it is economical to dedicate the SERA aircraft to a specific science mission. Its utility and value are enhanced by adding portholes, instrument mounts and power distribution capabilities.

The modern SERA airframe is constructed of low-maintenance, high-strength composite materials which are inherently light weight yet resistant to structural fatigue and corrosion. Because they are easy to shape and modify, very low-drag airframes have been introduced. The new lightweight and efficient aerodynamic design provides high performance from a relatively small engine. The resulting fuel economy reduces operating costs, increases the effective payload and/or extends operational range. For such high-strength aircraft, even extreme turbulence will not exceed design loads making airframe failure highly unlikely. More important, composite construction lends itself to the numerous airframe holes and hard-point instrument-mount modifications required to make the SERA a flexible research platform.

Although not all SERA’s have pusher engines, a small, low-drag airframe with a rear-mounted pusher engine have clear advantages for minimizing flow distortion and exhaust contamination (Crawford and Dobosy 1992). In concept, flow distortion and exhaust contamination can be minimized by placing the sensors on optimal locations on the airframe.

Flow distortion is a universal concern in research measurements and is especially problematic for high-quality turbulence measurements. In order to fly, an aircraft must generate strong flow distortion to overcome its weight and drag. The velocity and mass of air that the wings throw at the ground must equal the weight of the aircraft. As a result, this generates a strong upwash in front of the wing. Upwash magnitude is positively correlated with wing loading and the vertical wind velocity being measured (Crawford et al. 1996). Smaller airplanes, with light wing loading generate less upwash. With a pusher-type configuration, the center of gravity (CG), thus the main wing, is well aft of the aircraft nose. In general, the farther aft the wings, the weaker the upwash at the nose. As a result, this makes the nose an aerodynamically “clean” location to mount an instrument boom to measure wind, temperature, moisture, and pressure.

For air quality sampling (e.g., O_3, SO_2, particulate matter), great care must be taken to avoid the ingestion of engine exhaust into inlets that lead to air samplers. A pusher engine is desirable because it minimizes exhaust contamination since these corrupting influences are pushed to the rear of the aircraft.

Low flight-speed is another important advantage. First, small slow aircraft are very maneuverable and can safely fly close to the ground. This is important to many observations and critical if surface fluxes are to be observed. With increased altitudes, the surface signal becomes obliterated by turbulent mixing and flux divergence. Measurement accuracy and resolution decrease with increasing speed. For example, compression heating increases the observed temperature by square of the flight-speed. At a flight speed of 30 to 50 m s^{-1}, temperature corrections are small and manageable (~ 0.5 °C). For faster flying aircraft (> 100 m s^{-1}), temperature errors can exceed 5 °C. For many applications, this is a serious source of contamination which is difficult to remove (French et al. 2001).

2.3 *In Situ and Remote Sensors*

State-of-the-science sensors have become smaller, lighter, and consume less power. More important, many of these sensors can be operated with little or no supervision during flight. This evolution of *in situ* and remote sensors makes the SERA concept possible.

Central to any airborne measurement is knowing the location, orientation, and speed of the platform. While INS, OMEGA/VLF, and LORAN-C played an important roll in early aircraft systems, the advent of GPS technology has dramatically improved the accuracy and precision of wind velocity measurements. Numerous vendors produce GPS receivers that are lightweight, low-maintenance, and relatively low-cost. These systems can typically deliver useful data at a rate of 10 Hz. By using differential GPS (DGPS) correction techniques (i.e., collecting GPS data from a fixed station at a known location), aircraft position and horizontal velocity can be computed to within a few millimeters and ±1 cm s^{-1}, respectively (Lachapelle et al. 1992). Inexpensive, fast-response accelerometers provide a means to extend the frequency response (50 Hz) of position and velocity measurements (Crawford and Dobosy 1992). Accelerometer accuracy is quite high because the frequency range over which these sensors are used is rather small. A system such as the Trimble Advanced Navigation System (TANS) vector GPS can provide 10 Hz information on aircraft pitch, roll, and heading with an accuracy of 0.05°.

High-fidelity, fast-response sensors are necessary for acquiring turbulent flux measurements in the atmospheric boundary layer. The Best Aircraft Turbulence (BAT) probe is the centerpiece of the atmospheric measurement system (Crawford and Dobosy 1992; Hacker and Crawford 1999). Development of the BAT probe was the result of a collaboration of scientists and engineers from NOAA and Airborne Research Australia (ARA).

The BAT housing consists of a 15-cm diameter, carbon-fiber hemisphere mounted on a tapered boom. The hemisphere and boom are mounted on the nose of the aircraft. Nine pressure ports are symmetrically located on the hemisphere. Static and differential pressure are measured by four solid-state pressure sensors that have a frequency response of about 1 KHz and an accuracy of ±0.05 hPa. Wind velocities relative to the aircraft are computed from the pressure distributions observed over the array of pressure ports. In addition, air temperature measurements are acquired by redundant fast-response 0.13 mm micro-bead thermistors with a time response of 0.07 s. The pressure and temperature sensors, along with their respective electronics, are housed within the BAT probe. This allows the sensors to be interfaced in close proximity to signal conditioning electronics with no significant loss or contamination. Further, the sensors are heated to reduce temperature related drift.

Other *in situ* sensors should include an open-path infrared gas analyzer (IRGA) which measures turbulent fluctuations in water vapor and carbon dioxide at frequencies of 50 Hz (Auble and Meyers 1992).

Radiative fluxes can be measured with a variety of instruments to look at shortwave, longwave, broad-band and spectral radiances and irradiances. Typically these devices are quite small and require little power.

The SERA has an opportunity to play a significant role in air quality studies. For example, MetAir of Switzerland has instrumented a Dimona capable of providing basic aerosol properties and precursor gases (Neininger et al. 2001). NO_X, NO_Y, HNO_3, O_3, H_2O_2 are examples of parameters that can be measured. PMS probes are capable of measuring aerosol size spectra for particles larger than 0.1 :, while a three-wavelength integrating nephelometer can measure aerosol scattering coefficients. Devices such as the University of Wyoming CCN counter (Delene et al. 1998) illustrate that various types of instruments can be easily added to an already existing suite of aerosol instruments.

Boundary-layer studies often require some knowledge of the state of the Earth's surface. Recent advances in solid-state electronic technology have resulted in remote sensing devices that are lighter and use less power than those from a generation ago. It is now possible to carry both active and passive remote sensors on small aircraft.

For example, an array of three high-speed laser altimeters has been used to provide estimates of sea surface wave spectra for wavelengths longer than a few meters. The laser array consists of three downward looking lasers mounted in an equilateral triangle with 1-m separation. Two are mounted under either wing. The third is mounted under the fuselage of the aircraft. The lasers measure distance to ±2 mm. These lasers are complimented by a NASA-developed low-power Ka-band radar which provides estimates of mean surface slope over wave scales from 0.01 to 1 m. The use of the laser altimeters and Ka-band radar was a special configuration used for the Shoaling Waves Experiment (Crescenti et al. 1999; French et al. 2000).

2.4 *Data Acquisition and Processing*

The introduction of the microprocessor for instrument control, data acquisition, and processing has had a major impact on the measurement community. A modern PC with appropriate analog-to-digital (A/D) and input/output (I/O) hardware can easily be turned into a effective system controller and data logger. Execution of system and sensor control functions by software algorithms and instructions remove the need and expense of onboard operators and thereby significantly increases instrument payload and/or flight duration. An automated data control system allows precise timing of data acquisition from various analog and digital sensors. Regardless of sensor frequency and timing characteristics, a precise time series can be formatted and written in real-time to storage. The importance of writing a precise time series in flight is that it greatly reduces post flight data reduction efforts and improves data product accuracy. This is an essential aspect in the acquisition of turbulent flux data.

A custom data system may be built around a PC mother board which is simple and inexpensive to upgrade as technology advances. Data timing and synchronization is based on the highly-precise GPS time pulses. Analog signals are converted to digital signals by remote A/D modules that are synchronized to the GPS pulse. Each signal is high-pass filtered and then digitized to a resolution of 1 KHz. These data are then block-averaged to 50 Hz. Once the 50-Hz data are transferred to the computer, it is further block averaged, if necessary, and stored in a compressed binary data file on removable media. Our nominal configuration has 32 analog input channels available on two A/D modules. One module is mounted in the BAT probe housing and the other in the main computer. If more than 32 channels are required, additional modules are installed. A good design philosophy is to keep the data conversion as close to the sensors as possible.

Post flight data reduction is computationally complex and demanding. Fortunately, powerful data processing techniques are now possible on PC's. This enhanced computational power has allowed an important improvement in processing philosophy.

Typically, fast sensors have poor accuracy and accurate sensors are slow. It is desirable to digitally mix the two sensors to obtain high accuracy over broad frequency response. In the past this was done with causal filters to minimize computational demands. Unfortunately, such filters are one-sided and cause phase shifts. With powerful computers, spectral techniques are easily applied. One simply converts the data to spectral space with a fast Fourier transform (FFT), adds the desirable spectral components, and reconstitutes the data with an inverse FFT. Crawford and Dobosy (1992) discuss this concept as applied to obtain high fidelity position, velocity and attitude from differential acceleration and GPS.

3. SERA EXAMPLES

We will briefly focus on two examples of a SERA: NOAA's LongEZ and ARA's Grob G109B. Other examples of a SERA (not discussed in this paper) include the SkyArrow 650 ERA (Dumas et al. 2001) and the Stemme S-10 and Dimona (Neininger et al. 2001).

3.1 *LongEZ (N3R)*

The LongEZ (Fig. 1) has been used extensively within NOAA since 1986 in more than 30 experiments to acquire data for a variety of environmental research projects (Doran et al. 1992; Crawford et al. 1993, 1996; Brooks et al. 1997; Dobosy et al. 1997; Sun et al. 1997; Oechel et al. 1998). The LongEZ is constructed entirely from fiber composite. It is noted as a safe and reliable experimental category aircraft with exceptional performance. As a SERA platform, it has important safety, efficiency, and utility characteristics. The forward lifting surface, called a canard is designed to prevent the main wing from stalling. To enhance performance, the design also combines vertical winglets, laminar flow wings, and a pusher engine. Its unusual aerodynamic design makes it ideally suited for making high-fidelity turbulence measurements with minimal flow distortion at low altitudes and slow aircraft speeds. The departure of the LongEZ design from that of a standard airplane is obvious, often arousing public interest during field experiments. Far more than just being visually striking, these design features are ideal for environmental research measurements, especially at lower altitudes. For example, the distinct advantage of the small canard and pusher engine is apparent in that it allows for the mounting of instruments on the aircraft nose minimizing flow distortion, engine vibration, and exhaust. On the LongEZ, the wind measurement probe is five wing-widths (chord lengths) ahead of the canard. The resulting flow distortion is extremely low compared to other aircraft (Crawford et al., 1996).

Another important characteristic of a canard aircraft is that it penetrates turbulence far better than a conventional aircraft of the same wing loading (weight per unit wing area). Since the canard contributes both lift and stability, it can be heavily loaded, relative to the main wing. Therefore, an up-gust striking the wings causes more lift on the far aft main wing. The pitch response is down which damps response to the up-gust. If an up-gust strikes the rear-mounted elevator on a conventional airplane, control surface deflection imparts upward pitch response. This increases the lift generated by the wings and amplifies the response to gust. Canard airplanes, in contrast, have their elevators forward of the CG. Upward deflection of the elevator by an up-gust thus imparts a compensating downward pitch response. The pitch response to either up- or down-gust is opposed to the gust direction, giving canard aircraft their superior turbulent penetration characteristics. A canard-configured airplane is also stall-resistant. As the angle of attack of the airplane is increased, the canard stalls before the main wing. This causes the nose to drop, which decreases the angle-of-attack, providing automatic stall recovery without ever allowing the main wing to stall. The flexibility and damping of the fiber/foam composite structure used in these modern designs also "softens" the impact of the turbulence on the airframe.

The utility of the LongEZ as a SERA is illustrated by its impressive specifications and performance. There are few aircraft which will carry its own weight as payload. Typically, it will fly a research mission at 50 m s^{-1} using only 15 l hr^{-1} of fuel. Its fast cruise speed and long range allow it to reach anywhere where in the world. For its use as a SERA platform, it has been modified with redundant high-output alternators, extended fuel tanks, large engine, and numerous portholes to mount various instruments. These modifications enhance its utility as a SERA and were simple to install because of its fiber-composite construction and experimental airworthiness category.

Figure 1. The LongEZ (N3R) at First Flight Airport in Kill Devil Hills, North Carolina.

This aircraft has proven to be especially effective in studying the spatial variability of air-surface exchange and the transport and diffusion of material in the environment (e.g., Crawford et al. 1993; Sun et al. 1997; Vogel and Crawford 1999). The instrument suite and data acquisition system are used to measure mean properties of the atmosphere as well as turbulent fluxes of heat, moisture, momentum, carbon dioxide, ozone, and other quantities. Remote sensors such as laser altimeters and a Ka-band radar were recently added to determine wave field properties of the ocean.

3.2 *Grob G109B*

Since 1984, the Flinders University of South Australia and ARA have operated a Grob G109B (Fig. 2) motorized glider as a multi-purpose research aircraft (Hacker and Schwerdtfeger, 1997).

The G109B is another fiber-composite aircraft and is powered by a single 90-HP piston engine, based on a conversion of a 2.5 l automotive engine, and can carry a load of about 300 kg, including fuel and crew. As a motorized glider, the G109B has a rather large wing span (18 m). Its maximum take-off weight is 870 kg, typical cruising speed is 35 to 45 m s^{-1}. The aircraft is equipped with a comprehensive and modular set of instrumentation for a wide range of measurements as well as a data acquisition and real-time monitoring system. The G109B has participated in more than 40 stand-alone and collaborative field experiments in all parts of Australia.

Figure 2. The Grob 109B in flight.

The main purpose of the G109B and its instrumentation is to carry out low level surveys, measuring primarily the turbulent fluxes of sensible heat, latent heat, momentum, and a number of chemical quantities. Due to the aircraft's “clean” glider-derived aerodynamics, it is well suited for flying low and slow, a prime requirement for the type of research mentioned above. The G109B normally carries a crew of two, a pilot/scientist and a scientist/systems operator, but can also be operated by the pilot alone. It is capable of staying airborne (under power) for more than 10 hr, giving it a range of up to 1500 km, depending on the mission profile. Its normal operating altitude ranges from a few meters above the Earth's surface to about 3 km. It can operate from almost any type of airfield or airstrip including unprepared landing grounds. Permitted flight conditions are normally limited to daylight hours and outside of cloud (VFR). The G109B can be shipped in a specially-designed shipping container to anywhere in the world.

The aircraft is fitted with underwing instrumentation pods as well as hard points at numerous locations (wing tips, tail area, underneath and above the cockpit) with tubular ducts leading to these locations. If required, users can be supplied with empty custom-designed underwing pods in order to fit their own instrumentation.

The instrumentation flown on the G109B is extensive. This allows it to participate in a wide range of research projects, including studies of evaporation from lakes, coastal zones or different types of vegetation; studies of severe turbulence caused by early morning downslope wind; studies of the structure of sea breezes; studies of the exchange of trace gases between the atmosphere and vegetation; studies of the aerosol content of the atmosphere (using radiometric methods); instrumentation trials (GPS positioning and aircraft attitude systems); surveys of animal populations; aerial photography and filming; truthing of ground-based and satellite instrumentation and sensor arrays; structure of the atmospheric boundary layer; and structure of atmospheric turbulence elements.

4. VISION OF THE FUTURE

The SERA will fill a strategic niche by exploiting a low-cost, high-utility aircraft that is an ideal platform to carry state-of-the science *in situ* and remote sensors. These sensors are becoming smaller, lighter, and consume less power. At the same time, the cost of these sensors has decreased while their overall reliability has improved. The LongEZ and Grob G109B are two examples of well proven and cost-efficient airborne measurement systems capable of acquiring high-fidelity data.

Unfortunately, only a few scientists and organizations have taken advantage of the SERA concept. While a SERA is a effective and cost efficient tool, it requires a special mix of personnel who are knowledgeable in atmospheric processes, electrical and aerodynamic engineering, flying, and computer literacy. Putting together a small team with these skills can be a challenge. Another challenge is trying to implement start-up SERA programs. How best to execute this is yet to be resolved.

However, it is clear the future of airborne geoscience is changing with tightening budgets and limited access to expensive large aircraft. Increased awareness of growing pollution and environmental problems has led to new opportunities for SERA research programs. Such operations will be a vital component of future research programs assessing the Earth's climate, state-of-health, and habitability. Indeed, as environmental scientists, we should employ the most efficient, least intrusive and least expensive aircraft which can carry out the mission objective.

5. REFERENCES

Auble, D. A., and T. P. Meyers, 1992: An H_2O and CO_2 open-path gas analyzer for use with eddy flux systems. *Bound.-Layer Meteor.*, **59**, 243-256.

Borys, R. D., K. Tan, and W. Cotton, 1983: Ultralight sounder: an airborne system for studying the planetary boundary layer. *Bull. Amer. Meteor. Soc.*, **64**, 338-345.

Brooks, S. B., T. L. Crawford, and W. C. Oechel, 1997:

Measurement of carbon dioxide emissions plumes from Prudhoe Bay, Alaska oil fields. *J. Atmos. Chem.*, **27**, 197-207.

Dumas, E. J. ,Brooks, S., E., and J. Verfaillie, Jr., 2001: Development and testing of a Sky Arrow 650 environmental research aircraft. *Eleventh Symposium on Meteorological Observations and Instrumentation*, Albuquerque, NM, Amer. Meteor. Soc., paper 5.8.

Crawford, T. L., and R. J. Dobosy, 1992: A sensitive fast-response probe to measure turbulence and heat flux from any airplane. *Bound.-Layer Meteor.*, **59**, 257-278.

Crawford, T. L., R. T. McMillen, T. P. Meyers, and B. B. Hicks, 1993: Spatial and temporal variability of heat, water vapor, carbon dioxide, and momentum air-sea exchange in a coastal environment. *J. Geophys. Res.*, **98**, 12869-12880.

Crawford, T. L., R. J. Dobosy, and E. J. Dumas, 1996: Aircraft wind measurement considering lift-induced upwash. *Bound.-Layer Meteor.*, **80**, 79-94.

Crescenti, G. H., T. L. Crawford, and E. J. Dumas, 1999: Data report: LongEZ (N3R) participation in the 1999 Shoaling Waves Experiment (SHOWEX) pilot study. NOAA Tech. Memo. ERL ARL-232, Silver Spring, MD, 86 pp.

Delene, D. J., T. Deshler, P. Wechsler, and G. Vali, 1998: A balloon-borne cloud condensation nuclei counter. *J. Geophys. Res.*, **103**, 8927-8934.

Dobosy, R. J., T. L. Crawford, J. I. MacPherson, R. L. Desjardins, R. D. Kelly, S. P. Oncley, and D. H. Lenschow, 1997: Intercomparison among four flux aircraft at BOREAS in 1994. *J. Geophys. Res.*, **102**, 29101-29111.

Doran, J. C., F. J. Barnes, R. L. Coulter, T. L. Crawford, D. D. Baldocchi, L. Balick, D. R. Cook, D. Cooper, R. J. Dobosy, W. A. Dugas, L. Fritschen, R. L. Hart, L. Hipps, J. M. Hubble, W. Gao, R. Hicks, R. R. Kirkham, K. E. Kunkel, T. J. Martin, T. P. Meyers, W. Porch, J. D. Shannon, W. J. Shaw, E. Swiatek, and C. D. Whiteman, 1992: The Boardman Regional Flux Experiment. *Bull. Amer. Meteor. Soc.*, **73**, 1785-1795.

French, J. R., G. H. Crescenti, T. L. Crawford, and E. J. Dumas, 2000: LongEZ (N3R) participation in the 1999 Shoaling Waves Experiment (SHOWEX). NOAA Data Rep. OAR ARL-20, Silver Spring, MD, 51 pp.

French, J. R., T. L. Crawford, and R. C. Johnson, 2001: A high-resolution temperature probe for airborne measurements. *Eleventh Symposium on Meteorological Observations and Instrumentation*, Albuquerque, NM, Amer. Meteor. Soc., paper 5.10.

Hacker, J. M., and T. L. Crawford, 1999: The BAT-probe: The ultimate tool to measure turbulence from any kind of aircraft (or sailplane). *J. Tech. Soaring*, **XXIII**, 43-46.

Hacker, J. M., and P. Schwerdtfeger, 1997: An instrumented research aircraft for micrometeorological studies. *Windows on Meteorology, Australian Perspective*, E. K. Webb (Ed.), CSIRO Pub., Collinswood, Victoria, 342 pp.

Holmes, R. M., 1972: An airborne instrument system for atmospheric boundary layer research. *Bound.-Layer Meteor.*, **3**, 59-76.

Lachapelle, G., M. E. Cannon, and G. Lu, 1992: A comparison of P code and high performance C/A code GPS receiver for on the fly ambiguity resolution. *Bulletin Geodesique*, **67**, 185-192.

Lenschow, D.H., 1986: Aircraft measurements in the boundary layer. *Probing the Atmospheric Boundary Layer*, D. H. Lenschow, Ed., Amer. Meteor. Soc., 39-55.

Neininger, B., M. Baeumle, A. Volz-Thomas, A. S. H. Prévôt, and J. Dommen, 2001: A small aircraft for more than just ozone: Metair's aircraft after ten years of evolving development. *Eleventh Symposium on Meteorological Observations and Instrumentation*, Albuquerque, NM, Amer. Meteor. Soc., paper 5.7.

Oechel, W. C., G. L. Vourlitis, S. Brooks, T. L. Crawford, and E. Dumas, 1998: Intercomparison among chamber, tower, and aircraft net CO_2 and energy fluxes measured during the Arctic System Science Land-Atmosphere-Ice Interactions (ARCSS-LAII) flux study. *J. Geophys. Res.*, **103**, 28993-29003.

Sun, J., D. H. Lenschow, L. Mahrt, T. L. Crawford, K. J. Davis, S. P. Oncley, J. I. MacPherson, Q. Wang, R. J. Dobosy, and R. J. Desjardins, 1997: Lake-induced atmospheric circulations during BOREAS. *J. Geophys. Res.*, **102**, 29155-29166.

Vogel, C. A., and T. L. Crawford, 1999: Exchange measurements above the air-sea interface using an aircraft. *Air-Sea Exchange: Physics, Chemistry and Dynamics*, G. L. Geernaert, Ed., Kluwer Academic Publishers, 231-245.

Wyngaard, J. C., 1988: Effects of probe-induced flow distortion on atmospheric turbulence measurements extension to scalars. *J. Atmos. Sci.*, **45**, 3400-3412.

Wyngaard, J. C., L. Rockwell, and C. A. Friehe, 1985: Errors in the measurement of turbulence upstream of an axisymmetric body. *J. Atmos. Oceanic Technol.*, **2**, 605-614.

6. ADDITIONAL INFORMATION

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